

# Monitoring Carbon Dioxide Sequestration using Electrical Resistance Tomography (ERT): A Minimally Invasive Method

*R.L. Newmark, A.L. Ramirez, and W.D. Daily*

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# MONITORING CARBON DIOXIDE SEQUESTRATION USING ELECTRICAL RESISTANCE TOMOGRAPHY (ERT): A MINIMALLY INVASIVE METHOD

R.L. Newmark<sup>1</sup>, A. L. Ramirez<sup>1</sup> and W. D. Daily<sup>1</sup>

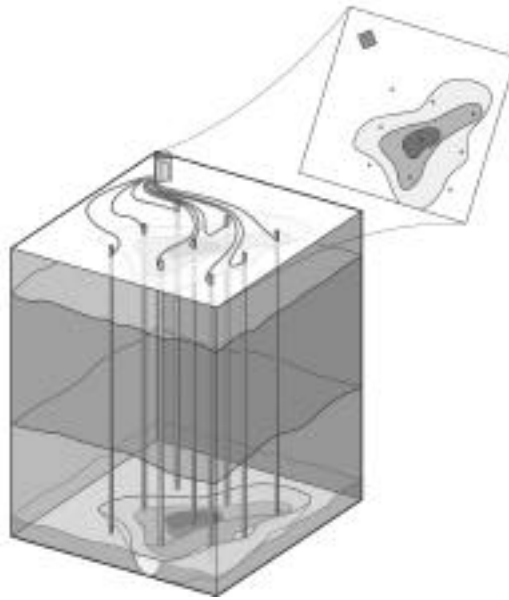
<sup>1</sup>Lawrence Livermore National Laboratory, Livermore, California, USA 94550

## ABSTRACT

Successful geologic sequestration of carbon dioxide (CO<sub>2</sub>), will require monitoring the CO<sub>2</sub> injection to confirm the performance of the caprock/reservoir system, assess leaks and flow paths, and understand the geophysical and geochemical interactions between the CO<sub>2</sub> and the geologic minerals and fluids. Electrical methods are especially well suited for monitoring processes involving fluids, as electrical properties are sensitive to the presence and nature of the formation fluids. High resolution tomographs of electrical properties are now used for site characterization and to monitor subsurface migration of fluids (i.e., leaking underground tanks, infiltration events, steam floods, contaminant movement, and to assess the integrity of engineered barriers). When electrical resistance tomography (ERT) imaging can be performed using existing well casings as long electrodes, the method is nearly transparent to reservoir operators, and reduces the need for additional drilling. Using numerical simulations and laboratory experiments, we have conducted sensitivity studies to determine the potential of ERT methods to detect and monitor the migration of CO<sub>2</sub> in the subsurface. These studies have in turn been applied to the design and implementation of the first field casing surveys conducted in an oil field undergoing a CO<sub>2</sub> flood.

## INTRODUCTION

Successful geologic sequestration of CO<sub>2</sub> will require monitoring both during active injection and for verification of long-term storage. Remote methods are desired, in order to minimize disruption and to reduce costs. Electrical methods are sensitive to both the presence and nature of formation fluids. The electrical properties of rocks and soils depend on water saturation, the amount and type of ions in the water, pH, cation exchange capacity of the minerals, and on temperature. Electrical resistance tomography (ERT) is a recent modality for imaging that is being used with increasing frequency for shallow subsurface imaging, for site characterization, and for monitoring fluid movement and subsurface processes [1,2,3,4,5,6,7]. High resolution ERT surveys are commonly conducted utilizing vertical arrays of point electrodes in a crosswell configuration (data processing has been described elsewhere [8,9,10,11]). However, for large-scale applications, point electrode surveys are less attractive due to economics. Point electrode arrays must be installed with direct contact between the electrodes and the formation; currently, they cannot be conducted through casing. In an ideal field design, the electrode spacing is smaller than the thickness of the features of interest, with the array length substantially greater than the well separation. These constraints make high resolution point electrode surveys impractical for implementation at oil reservoir scale.



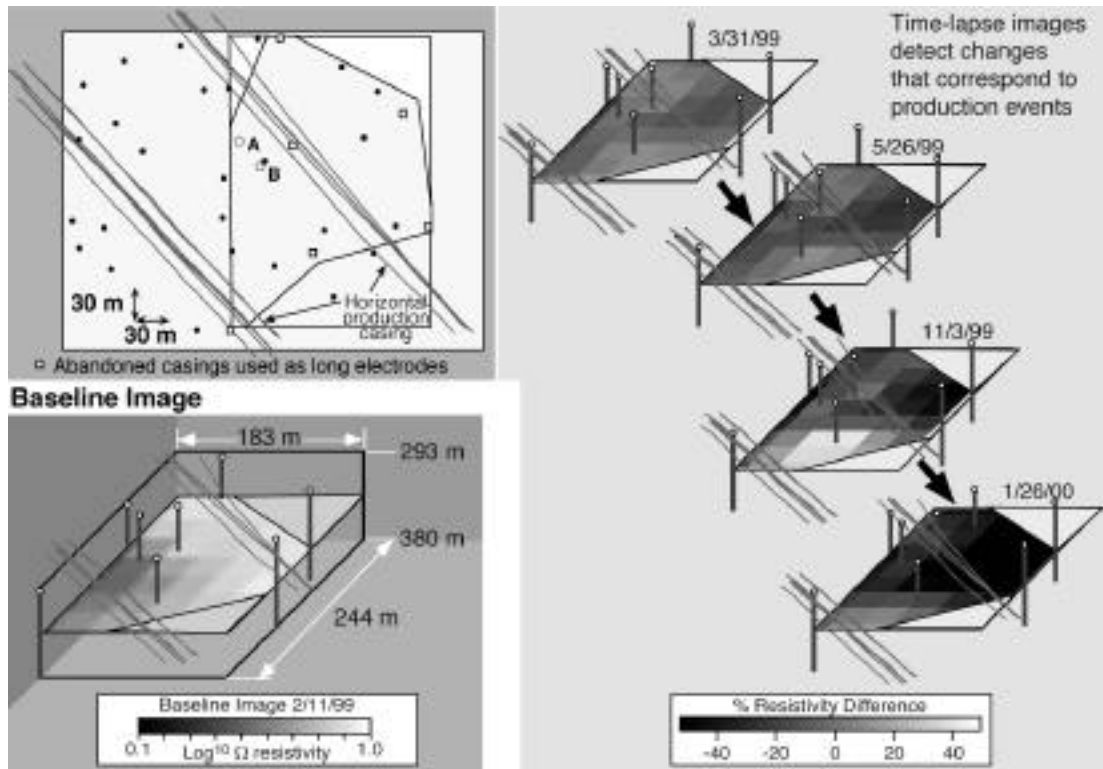
**Figure 1.** Casing surveys utilize the wells themselves as electrodes. The products are time dependent maps of the horizontal changes in formation resistivity.

Electrical surveys that use existing subsurface infrastructure in the field are an attractive alternative. The conductive metallic well casings can be used as long electrodes, thus permitting the same infrastructure to have a dual operational and monitoring role. In a casing survey, pairs of casings are energized as a transmitter, and potentials are measured across pairs of other, receiver casings (Figure 1). For a typical pattern, this results in a relatively sparse dataset, which produces a low resolution image. This concept was tested using abandoned steel casings in an oil field undergoing steam flood, where the mapped changes in the electrical properties were consistent with production events [12,13,14] (Figure 2). Ongoing work is focused on developing the ability to conduct such surveys while the casings are connected to surface piping and electrical under routine operations; this has both data quality and operational safety implications.

## APPROACH

Numerical simulations and physical modeling have been used to define the performance envelope of the ERT method prior to fielding. The predominant experience with ERT has been with targets displaying a decrease in resistivity; the ability to detect an electrically insulating target (such as CO<sub>2</sub>) has been less certain. Results of these initial studies have been directed toward the design of a field survey that is currently underway.

In a previous effort, Newmark, Ramirez and Daily [16,17] conducted numerical sensitivity studies to determine the sensitivity of the method to realistic changes in field conditions. Factors considered include resistivity contrast, anomaly proximity to electrodes, anomaly size and shape, measurement noise, and the electrode configuration used to perform the measurements. Simulations run assuming that electrically isolated well casings (disconnected from surface piping and electrical) used as long electrodes or with arrays of point electrodes (simulating high resolution surveys) provided useful monitoring information for a range of conditions, including narrow simulated CO<sub>2</sub> fingers.



**Figure 2.** Casing surveys obtained in an oil field undergoing steam flood. Six abandoned casings were used, along with two electrode arrays installed for high resolution surveys. The baseline survey indicates areas already affected by steam flood (through various vertical wells, shown as dots on the map), displaying lower resistivity. Decreases in resistivity in the difference images that intensify over time correspond to stimulation and production operations.

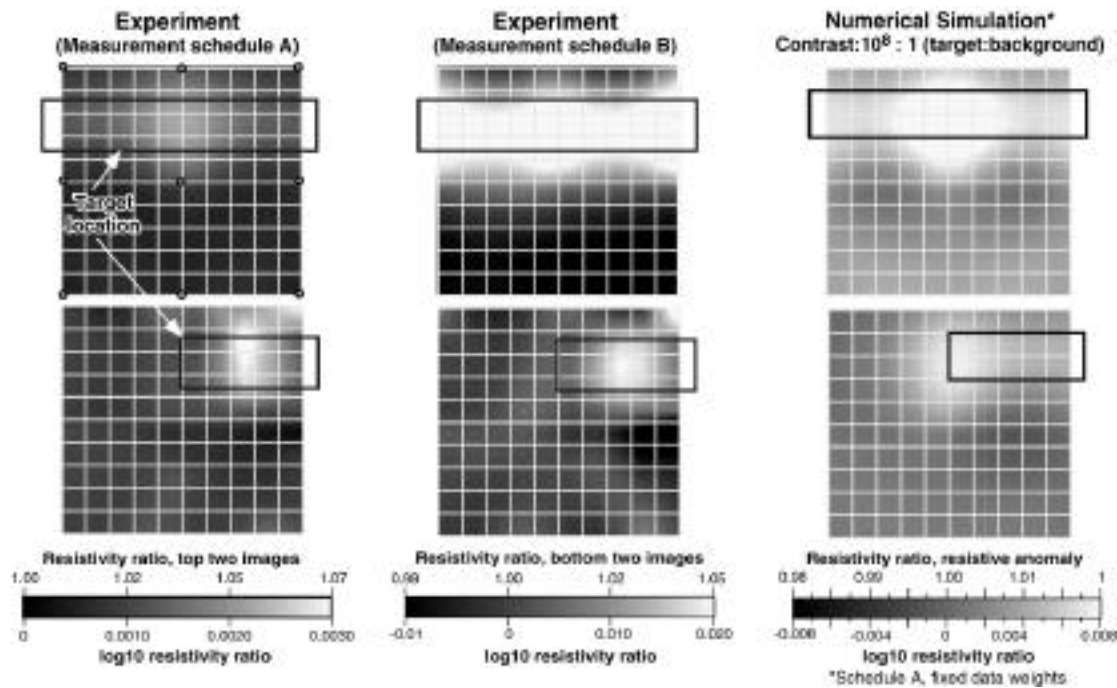
In recent efforts, physical, bench-scale models have been used to control experimental conditions such as the electrical conductivity of the background formation, the position and size of target anomalies, the electrical contrasts between target and background and the electrode configuration, including the use of vertical well casings as long electrodes. Physical models provide data with realistic data errors, which are absent in numerical simulation data (even when synthetic but unrealistic errors are included in the analysis). We compare the known physical models with the reconstructed images to evaluate the strengths and weakness of ERT under different conditions. These measurements form a link between numerical simulations and field surveys.

The laboratory tests were conducted in a 3.35 m diameter water tank in which measurements can be made on functional physical models. Water provides an ideal background of uniform conductivity in which to test different target and electrode configurations. Both point electrode arrays similar to those used in high resolution field surveys and long electrode configurations simulating the use of well casings as long electrodes were tested. Only the long electrode results for resistive targets will be discussed here. The experimental configuration consists of a nine-spot pattern of vertical copper rods extending 122 cm, forming a 50 cm square. Specific targets were introduced horizontally into the model, between two rows of electrodes. The cylindrical targets are 40.64 cm long and 5.72 cm diameter. Target materials tested include plexiglass, brass, steel wool, steel screen, aluminum and graphite.

The long electrode measurements should only reveal lateral changes in the model region (with only vertical electrodes, no vertical resolution is obtained). The results are map views, which represent vertical integrations through the model region (Figure 3). The anomalous region is located in the correct location, and it is of the correct direction of change in electrical properties. Its magnitude is not expected to accurately reflect the target properties, as these results represent the net change over the entire electrodes'

height. The long electrode images provide moderate lateral resolution for both conductive and resistive targets.

Numerical simulations were compared with the experimental results. Forward simulations of the physical experiments using plastic targets were run using a highly resistive contrast target of  $10^8:1$ , and tomographic images were reconstructed from the synthetic data. The results supplement the experimental results; anomalous regions are very similar in size, location and magnitude. These results indicate that the approximations made during processing (i.e., simulating the presence of the long electrodes themselves in the model) are acceptable, resulting in fair reproductions of the physical model.

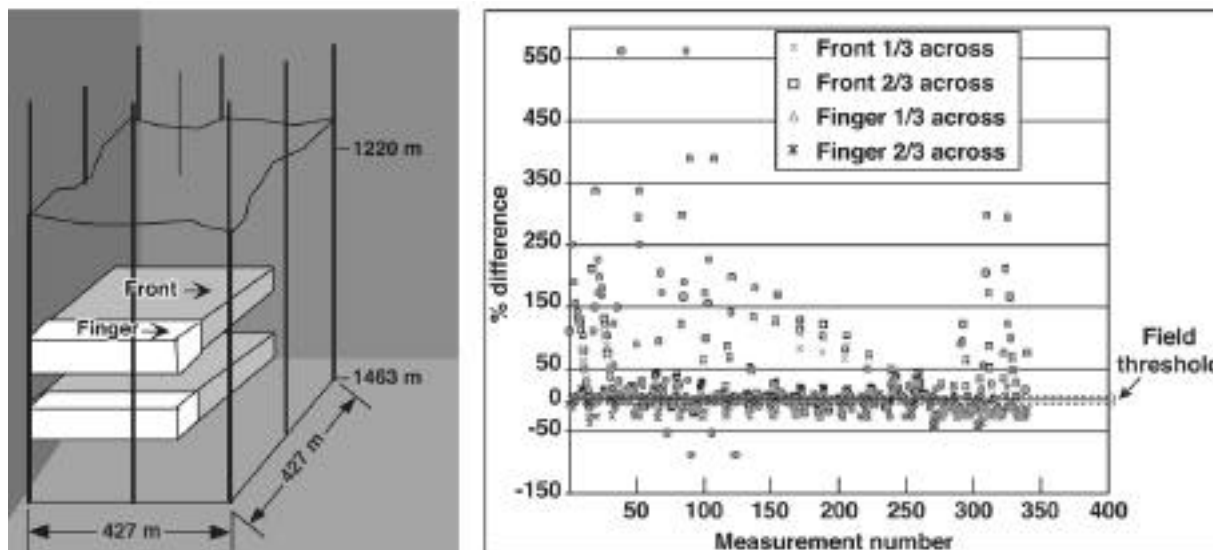


**Figure 3.** Experimental and numerical results for laboratory experiments with highly resistive (plastic) targets. Comparison of results obtained with different measurement schedules demonstrate the sensitivity to symmetry in acquisition design. In all cases, the target's location can be determined.

The laboratory results provide additional information regarding the fidelity with which ERT imaging can be expected to reproduce a resistive target. Tomograph degradation due to measurement errors and numerical modeling errors is relatively minimal. Anomalies are typically of somewhat larger size and lower contrast than the actual targets. These differences are due to the reconstruction algorithm's search for a smoothly numerical model of smoothly varying electrical conductivity. By comparing experimental and numerical results of point and long electrode surveys, we have identified previously undiscovered factors effecting ERT image fidelity. These include sensitivities to the symmetry of the measurement schedule, the need to explicitly include the casings themselves in the forward models, automated weighting of individual data, and the possible effect of induced polarization for certain materials used in the physical models. These results increase our confidence in our ability to predict ERT performance under field conditions.

Using results from the numerical simulations and laboratory results, a long electrode survey was designed for an oil field undergoing  $\text{CO}_2$  stimulation. Numerical simulations were run to assess the potential signal strength for realistic injection scenarios. We simulated the effects of two 15 m thick planar units with a five-fold increase in resistivity migrating one third and two thirds the distance across the model volume, as well as two finger-like units 15 m thick and 15 m wide migrating in the same manner (Figure 4). While the majority of measurements are of small value, many will result in significant % difference, with signal

strength substantially above the noise level of  $\pm 6\%$  difference measured at previous field sites. These results indicate sufficient signal to detect changes due to CO<sub>2</sub> migration.



**Figure 4.** Numerical simulations were used to design a field survey, now underway. Slab-like fronts and narrow fingers with 5-fold resistivity increases were modeled passing across a 9-spot casing configuration. For both geometries, there are a substantial number of measurement values above the field-measured signal to noise threshold.

An initial baseline casing survey was conducted in an oil field undergoing CO<sub>2</sub> flood. For these measurements, the wells were disconnected from surface electrical and piping. A subsequent casing survey has been conducted, in which the wells were connected to polyethylene surface piping and standard electrical. Data quality degradation was found to be minimal. Time-lapse surveys are planned to detect changes in the formation properties as CO<sub>2</sub> injection continues.

## SUMMARY OF RESULTS TO DATE

Combined numerical and laboratory studies demonstrate that resistive anomalies such as those resulting from CO<sub>2</sub> migration in a reservoir can be imaged using ERT. Anomalies are typically of larger size and lower contrast than the actual targets. This result is consistent with the properties of the reconstruction algorithm, which searches for the numerical model of smoothly varying electrical conductivity. The laboratory results indicate that tomograph degradation due to numerical modeling and measurement errors is minimal; both the numerical simulation and the laboratory results have similar features and are of comparable magnitude. Numerical simulations for a casing survey in an oil field undergoing CO<sub>2</sub> flood indicate sufficient signal to detect changes due to CO<sub>2</sub> migration. These results have been used to design a field survey, which is currently underway.

## ACKNOWLEDGEMENTS

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